TIME-ACCURATE AERODYNAMIC MODELING OF SYNTHETIC JETS FOR FLOW CONTROL

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ABSTRACT

This paper describes a computational study undertaken to determine the aerodynamic effect of tiny unsteady synthetic jets as a means to provide the control authority needed to maneuver a spinning projectile at low subsonic speeds. Advanced Navier-Stokes computational techniques have been developed and used to obtain numerical solutions for the unsteady jet-interaction flow field at subsonic speeds and small angles of attack. Unsteady numerical results show the effect of the jet on the flow field and on the aerodynamic coefficients. The unsteady jet is shown to substantially alter the flow field both near the jet and the base region of the projectile that in turn affects the forces and moments even at zero degree angle of attack. The results have shown the potential of computational fluid dynamics to provide insight into the jet interaction flow fields and provided guidance as to the locations and sizes of the jets to generate the maximum control authority to maneuver a projectile to hit its target with precision.

1. INTRODUCTION

Accurate determination of aerodynamics is critical to the low-cost development of new advanced munitions (Sahu1995; Sahu 1996). Competent smart munitions that can more accurately hit a target can greatly increase lethality and enhance survivability. Desert Storm convincingly demonstrated the value of large-scale precision-guided munitions. A similar capability for small-scale munitions would increase the effectiveness of the infantry units, reduce collateral damage, and reduce the weight of munitions that must be carried by individual soldiers. The Army is therefore seeking a new generation of autonomous, course-correcting, gun-launched projectiles for infantry soldiers. Due to small projectile diameter (20 to 40mm), maneuvers by canards and fins seem very unlikely. An alternate and new evolving technology is the micro-adaptive flow control through synthetic jets. These very tiny (approximately 0.3mm) synthetic micro-jet actuators have been shown to successfully modify subsonic flow characteristics and pressure distributions for simple airfoils and cylinders (Smith 1998; Amitay 1999). The synthetic jets are control devices (Figure 1) with zero net mass flux and are intended to produce the desired control of the flow field through momentum effects. In this case, fluid is pumped in and out of the jet cavity at a high frequency, of the order of 1000 Hz. Many parameters such as jet location, jet velocity, and jet actuator frequency can affect the flow control phenomenon. Up to now, the physics of this phenomenon has not been well understood and advanced numerical predictive capabilities or high fidelity computational fluid dynamics (CFD) design tools did not exist for simulation of these unsteady jets. However, the research effort described here has led to an advanced aerodynamic numerical capability to accurately predict and provide a crucial understanding of the complex flow physics associated the unsteady aerodynamics of this new class of tiny synthetic micro-jets for control of modern projectile configurations. High performance CFD techniques were developed and applied for the design and analysis of these Micro-Adaptive Flow Control systems for maneuvering a spinning projectile for infantry operations.

The control of the trajectory of a 40mm spinning projectile is achieved by altering the pressure distribution on the projectile through forced asymmetric flow separation. Unsteady or time-accurate CFD modeling capabilities were developed and used to assist in the design of the projectile shape, the placement of the synthetic actuators and the prediction of the aerodynamic force and moments for these actuator configurations. Additionally, the advanced CFD capabilities provided a simpler way to explore various firing sequences of the actuator elements. Time-accurate unsteady CFD computations were performed to predict and characterize the unsteady nature of the synthetic jet interaction flow field produced on the M203 grenade launched projectile for various yaw and spin rates for fully viscous turbulent flow conditions. Turbulence was initially modeled using a traditional Reynolds-Averaged Navier-Stokes (RANS) approach. Although, this approach provided some detailed flow physics, it was found to be less accurate for this new class of unsteady flows associated with synthetic jets. In order to improve the accuracy of the numerical simulation, the predictive capability was extended to include a higher order hybrid RANS/LES (Large Eddy Simulation) approach (Arunajatesan 2000; Batten 2000). This new approach computed the large eddies present in the turbulent flow structure and allowed the simulation to capture with high fidelity additional flow structures associated the synthetic jet interactions in a time-dependent fashion. Modeling of azimuthally placed synthetic micro-jets required tremendous grid resolution, highly specialized boundary conditions for the jet activation, and the use of

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **00 DEC 2004**	2. REPORT TYPE **N/A**	3. DATES COVERED -
4. TITLE AND SUBTITLE **Time-Accurate Aerodynamic Modeling Of Synthetic Jets For Flow Control**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **U.S. Army Research Laboratory Aberdeen Proving Ground, MD 21005-5066**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM001736, Proceedings for the Army Science Conference (24th) Held on 29 November - 2 December 2005 in Orlando, Florida. , The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**8**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

advanced hybrid LES approach permitting local resolution of the unsteady turbulent flow with high fidelity.

The addition of yaw and spin while the projectile is subjected to the pulsating micro-jets rendered predicting forces and moments a major challenge. The Department of Defense High Performance Computing Modernization Office (HPCMO) selected this research as a grand challenge project and provided the massive computational resources required by these unsteady time-accurate simulations. The new capability has been demonstrated and this technology has recently been successfully applied to the self-correcting projectile for infantry operations (SCORPION) program.

2. COMPUTATIONAL METHODOLOGY

The complete set of three-dimensional (3-D) time-dependent Navier-Stokes equations (Pulliam 1982) is solved in a time-accurate manner for simulations of unsteady synthetic jet interaction flow field on the M203 grenade launched projectile with spin. The 3-D time-dependent RANS equations are solved using the finite volume method (Peroomian 1997; Peroomian 1998):

$$\frac{\partial}{\partial t}\int_V \mathbf{W}dV + \oint[\mathbf{F}-\mathbf{G}]\cdot dA = \int_V \mathbf{H}dV \qquad (1)$$

where $\mathbf{W}$ is the vector of conservative variables, $\mathbf{F}$ and $\mathbf{G}$ are the inviscid and viscous flux vectors, respectively, $\mathbf{H}$ is the vector of source terms, V is the cell volume, and A is the surface area of the cell face.

Second-order discretization was used for the flow variables and the turbulent viscosity equations. Two-equation (Goldberg 1997) and higher order hybrid RANS/LES (Batten 2000) turbulence models were used for the computation of turbulent flows. The hybrid RANS/LES approach based on Limited Numerical Scales (LNS) is well suited to the simulation of unsteady flows and contains no additional empirical constants beyond those appearing in the original RANS and LES sub-grid models. With this method a regular RANS-type grid is used except in isolated flow regions where denser, LES-type mesh is used to resolve critical unsteady flow features. The hybrid model transitions smoothly between an LES calculation and a cubic k-ε model, depending on grid fineness. A somewhat finer grid was placed around the body and near the jet; the rest of the flow field was modeled with a coarser, RANS-like mesh. Dual time-stepping was used to achieve the desired time-accuracy. In addition, special jet boundary conditions were developed and used for numerical modeling of synthetic jets. The grid was moved computationally to take into account the spinning motion of the projectile.

3. PROJECTILE GEOMETRY AND COMPUTATIONAL GRID

The projectile used in this study is a 1.8-caliber ogive-cylinder configuration (see Figure 2). Here, the primary interest is in the development and application of CFD techniques for accurate simulation of projectile flow field in the presence of unsteady jets. The first step was to obtain a converged solution for the projectile without the jet. This converged jet-off solution was then used as the starting condition for the computation of the time-accurate unsteady flow field for the projectile with synthetic jets. The jet locations on the projectile are shown in Figure 3. The jet width was 0.32 mm and the jet slot half-angle was 18^o. The jet conditions were specified at the exit of the jet for the unsteady (sinusoidal variation in jet velocity) jets. The jet conditions specified include the jet pressure, density and velocity components. The peak jet velocities used were 31 and 69 m/s operating at a frequency of 1000 Hz.

Figure 4 shows an expanded view of the computational grid near the vicinity of the projectile. Grid points are clustered near the jet as well as the boundary layer regions to capture the high gradients flow regions. The computational grid has 211 points in the streamwise direction, 241 in the circumferential direction, and 80 in the normal direction. Numerical computations have been made for these jet cases at subsonic Mach numbers, M = 0.11 and 0.24 and at angles of attack, $\alpha = 0^o$ to 4^o. These unsteady simulations took thousands of hours of CPU time on Silicon Graphics Origin and IBM SP3 computers running with 16–24 processors.

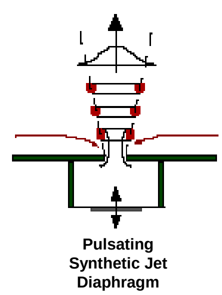

Fig. 1. Schematic of a synthetic jet.

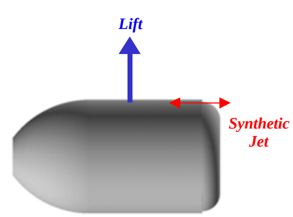

Fig. 2. Projectile geometry.

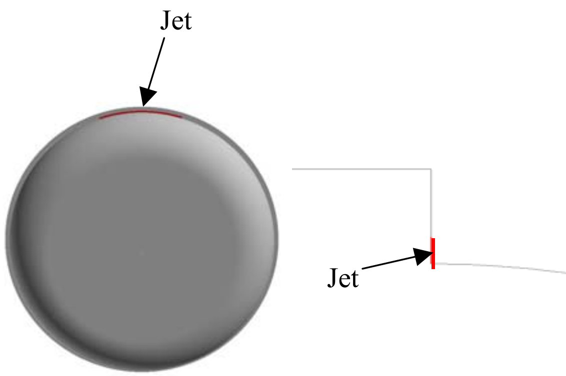

Fig. 3. Aft-end geometry showing the jet location.

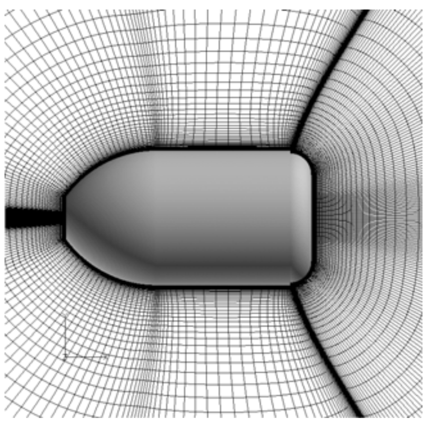

Fig. 4. Computational grid near the projectile.

4. RESULTS

Time-accurate unsteady numerical computations using advanced viscous Navier-Stokes methods were performed to predict the flow field and aerodynamic coefficients on both a non-spinning and a spinning projectile. Limited experimental data (Rinehart 2002; McMichael 2003) exists only for the non-spinning case and was used to validate the unsteady CFD results.

4.1 Non-spinning Projectile Case

Three-dimensional unsteady CFD results were obtained at a subsonic Mach number of 0.11 and several angles of attack from 0° to 4° using both RANS and the hybrid RANS/LES approaches. These 3-D unsteady CFD results have provided fundamental understanding of fluid dynamics mechanisms associated with the interaction of the unsteady synthetic jets and the projectile flow fields. Many flow field solutions resulting from the simulation of multiple spin cycles and, hence, a large number of synthetic jet operations, were saved at regular intermittent time-intervals to produce movies to gain insight into the physical phenomenon resulting from the synthetic jet interactions. The unsteady jets were discovered to break up the shear layer coming over the step in front of the base of the projectile. This created a delay in the flow to separate at the base resulting asymmetric flow separation (between the top and bottom). It is this insight that was found to substantially alter the flow field (making it highly unsteady) both near the jet and in the wake region that in turn produced the required forces and moments even at zero degree angle-of-attack (level flight). Time-accurate velocity magnitude contours (Figures 5 and 6) confirm the unsteady wake flow fields arising from the interaction of the synthetic jet with the incoming free stream flow at Mach = 0.11.

Figure 7 shows the particles emanating from the jet and interacting with the wake flow making it highly unsteady. More importantly, the break up of the shear layer is clearly evidenced by the particles clustered in regions of flow gradients or vorticity (evident in computed pressure contours, Fig. 8). Verification of this conclusion is provided by the excellent agreement between the predicted (solid line) and measured (Rinehart 2002) (solid symbols) values of the net lift force due to the jet (Fig. 9). The net lift force (Fy) was determined from the actual time histories of the highly unsteady lift force (an example shown in Fig. 10 for various angles of attack) resulting from the jet interaction at zero degree angle of attack and computed with the new hybrid RANS/LES turbulence approach.

4.2 Spinning Projectile Case

Here, the projectile (40mm grenade) spins clockwise at a rate of 67 Hz looking from the front of the projectile (see Figure 11). The jet actuation corresponds to one-fourth of the spin cycle from -45° to +45° with zero degree being the positive y-axis. The jet is off during the remaining three-fourths of the spin cycle. The unsteady CFD modeling required about 600 time steps to resolve a full spin cycle. For the part of the spin cycle when the jet is on, the 1000 Hz jet operated for approximately for four cycles. The actual computing time for one full spin cycle of the projectile was about 50 hours using 16 processors (i.e. 800 processor-hours) on an IBM SP3 system for a mesh size about four million grid points. Multiple spin cycles and, hence, a large number of synthetic jet operations, were required to reach a periodic time-accurate unsteady solution. As will be seen later, some cases were run for as many as 60 spin cycles requiring over 48,000 processor hours of computer time.

Computed particle traces (colored by velocity) emanating from the jet into the wake are shown in Figure 12 for a given instant in time at M = 0.24 and α = 0°. The particle traces emanating from the jet interact with the wake flow making it highly unsteady. It shows the flow in the base region to be asymmetric due to the interaction of the unsteady jet.

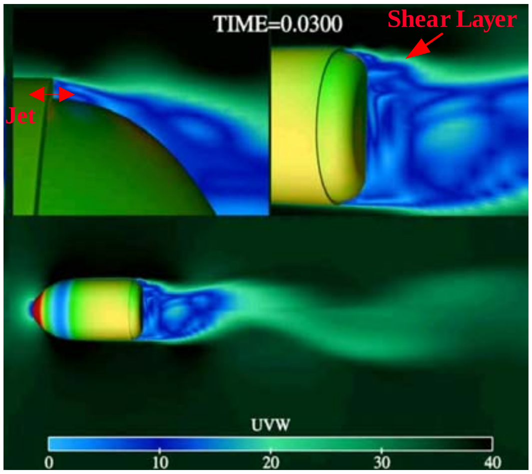

Fig. 5. Velocity magnitudes, M=0.11, α = 0°

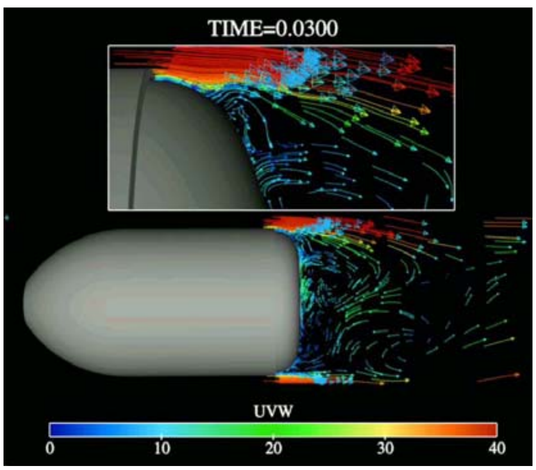

Fig. 6. Velocity vectors, M = 0.11, α = 0°.

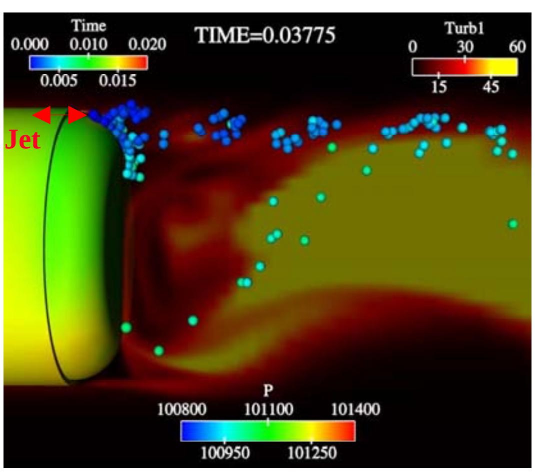

Fig. 7. Particle Traces, M = 0.11, α = 0°

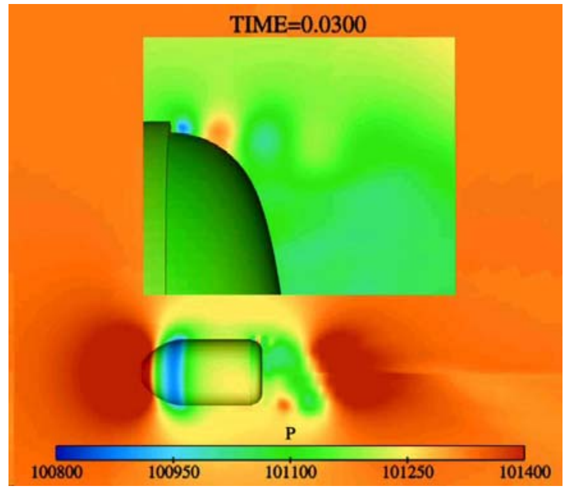

Fig. 8. Computed Pressures, M = 0.11, α = 0°.

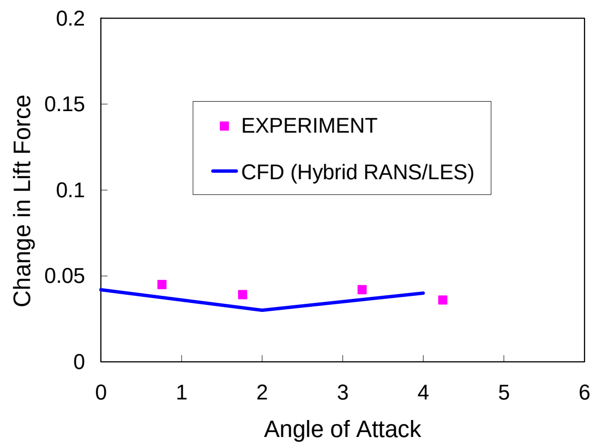

Fig. 9. Computed change in lift force due to jet at various angles of attack, M = 0.11.

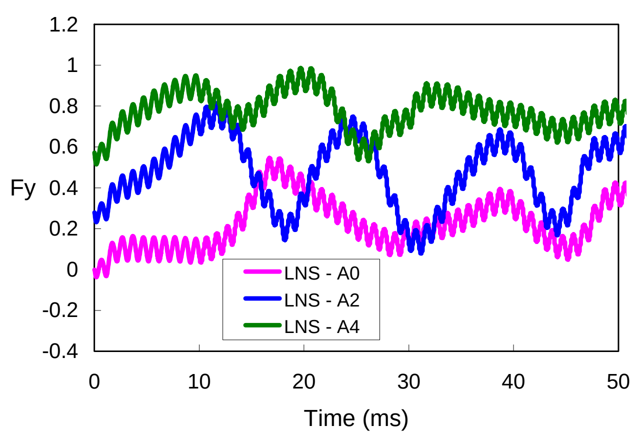

Fig. 10. Computed lift force for various angles of attack, M = 0.11.

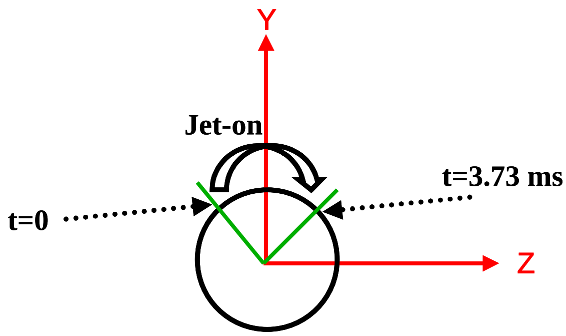

Fig. 11. Schematic showing the jet actuation in one spin cycle (view from the front or the nose).

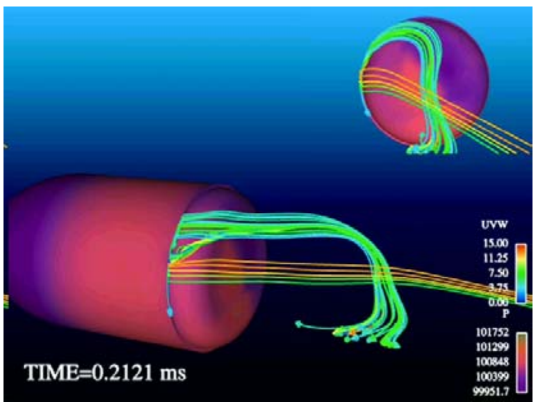

Fig. 12. Computed particle traces colored by velocity, jet-on, M = 0.24, α = 0°.

The computed surface pressures from the unsteady flow fields were integrated to obtain the aerodynamic forces and moments (Sahu 2003) from both unsteady RANS (URANS) as well as the hybrid RANS/LES (also referred to as LNS) approach. The jet-off unsteady RANS calculations were obtained first and the jets were activated beginning at time, t = 28 ms. Computed normal or lift force (F_Y) and side force (F_Z) were obtained for two different jet velocities, Vj = 31 and 69 m/s and are shown in Figure 13 for the larger jet velocity as a function of time at Mach, M = 0.24 and α = 0°. These computed results, obtained with the URANS approach, clearly indicate the unsteady nature of the flow field. When the jet is on, one can clearly see an increase in the lift force resulting from the jet activation. When the jet is turned off, the levels of this lift force drops to the same levels prior to the jet activation, corresponding to the jet-off wake flow. Figure 14 shows the comparison of the predicted lift force using URANS and LNS models. Unlike the LNS approach, the URANS result clearly shows when the jet is on and when it is off during the spin cycle. Of course what is more important is the actual level of the lift force predicted the different models. As described earlier, the comparisons for the non-spinning cases showed that the level of lift force predicted by LNS closely matched the data. Here, the addition of spin as well as the jet actuation for part of the spin cycle further complicates the analysis of the CFD results for the LNS case. The level of oscillations seen is quite large and the effect of the jet cannot be easily seen in the instantaneous time histories of the unsteady forces and moments. To get the net effect of the jet, unsteady computations were run for many spin cycles of the projectile with the synthetic jets. The CFD results are plotted over only one spin cycle. Each subsequent spin cycle was superimposed and a time-averaged result was then obtained over one spin cycle. In all these cases, the jet is on for one-fourth of the spin cycle (time, t=0 to 3.73 ms) and is off for the remainder (three-fourths) of the spin cycle. One can now examine the time-averaged results to gain insight into the time-dependent jet interactions and their effects on the aerodynamic forces.

Figures 15 through 16 show the time-averaged results over a spin cycle. Figure 15 shows the computed lift force again averaged over many spin cycles for the peak jet velocity of 69 m/s. The jet effect can clearly be seen when the jet is on (t=0 to 3.73 ms) even after 5 or 10 spin cycles. The net lift is about 0.17 Newton due to the jet actuation and seems to have converged after 20 spin cycles. For the remainder of the spin cycle, the jet is off; however, the effect of the jet on the wake still persists and this figure shows that lift force (with a mean value of 0.07 Newton) is still available. We expected a lift force contribution when the jet was on; however, the fact that we are seeing a contribution to the lift force when the jet is off was totally unexpected. These time-accurate CFD results are first of its kind to show such an effect due to the wake interactions. The new insight provided by the time-averaged CFD results for the spinning projectile is extremely difficult, if not impossible, to obtain by any other means.

Figure 16 shows the computed averaged lift force after 50 and 60 spin cycles for jet velocities 31 and 69 m/s, respectively. It clearly shows that the larger jet producing larger lift force than the smaller jet when the jet is activated. A parameter of interest is the net impulse that results from the unsteady jet interactions. The computed lift force can be integrated over time to obtain the impulse. Figure 17 shows the impulse obtained from the lift force as a function of the spin cycles for both jets. In both cases, it takes about 30 to 40 spin cycles before the impulse asymptotes to a fixed value. This indicates that large amount of computing resources are required for these time-accurate CFD computations for spinning bodies. The computed lift force along with other aerodynamic forces and moments, directly resulting from the pulsating jet, were then used in a trajectory analysis (Costello 2003). As shown in Figure 18, the synthetic micro-jet produced a substantial change in the cross range that can provide the desired course correction for the projectile to hit its target.

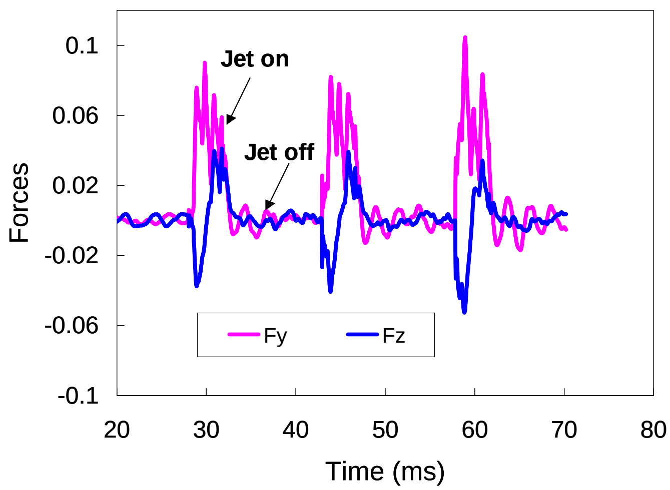

Fig. 13. Computed lift and side forces, URANS, M = 0.24, Vj = 69 m/s, α = 0°.

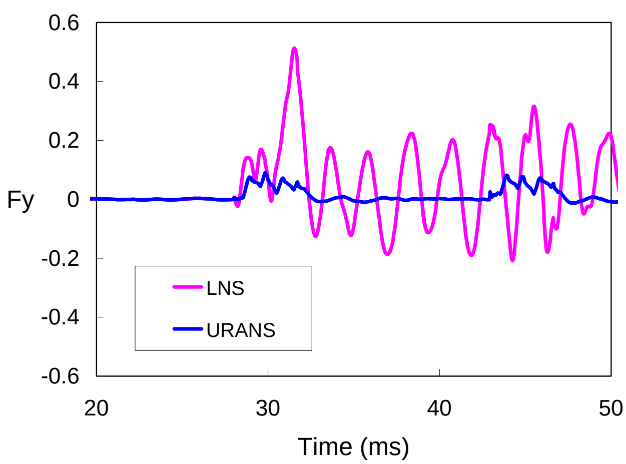

Fig. 14. Computed lift forces, URANS and LNS, M = 0.24, Vj = 69 m/s, α = 0°.

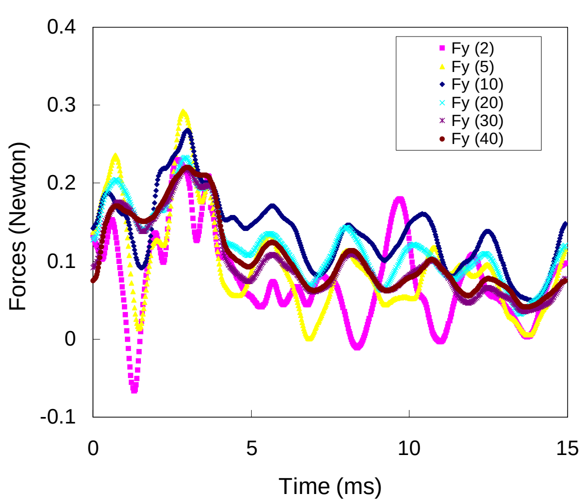

Fig. 15. Computed lift force over many spin cycles, LNS, Vj = 69 m/s, M = 0.24, α = 0°, Spin = 67 Hz.

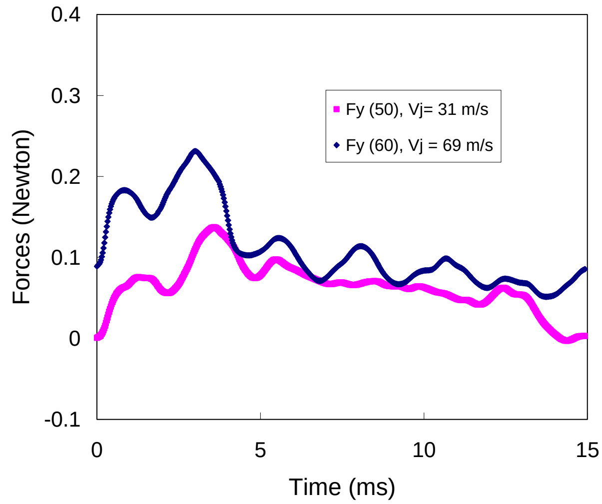

Fig.16. Computed lift force over many spin cycles for two jet velocities, LNS, M = 0.24, α = 0°, Spin = 67 Hz.

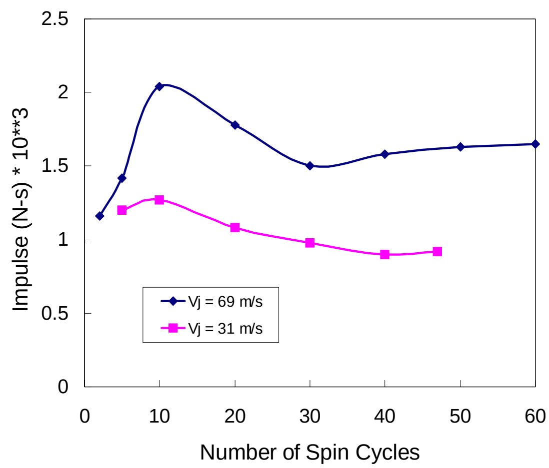

Fig. 17. Impulse from the lift force vs. spin cycles for two jet velocities, M = 0.24, α = 0°, Spin = 67 Hz

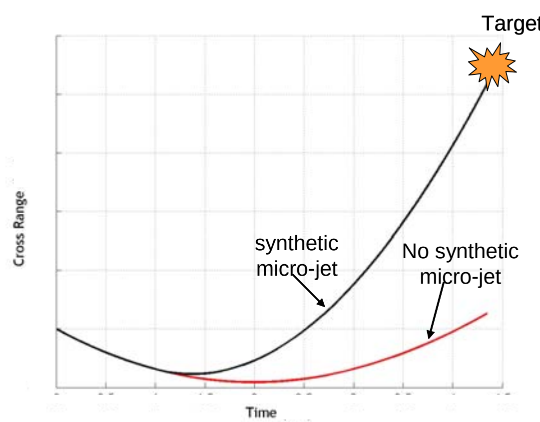

Fig. 18. Synthetic jet control on the flight trajectory.

CONCLUSION

This paper describes a computational study undertaken to determine the aerodynamic effect of tiny synthetic jets as a means to provide the control authority needed to maneuver a projectile at low subsonic speeds. Computed results have been obtained for a subsonic projectile for both non-spinning and spinning cases using time-accurate Navier-Stokes computational techniques and advanced turbulence models. The unsteady jet in the case of the subsonic projectile is shown to substantially alter the flow field both near the jet and the base region that in turn affects the forces and moments even at zero degree angle of attack. The hybrid RANS/LES computations predicted the changes in lift force due to the jet which matched well with the experimental data for various angles of attack from 0° to 4°. For the spinning projectile cases, the net *time-averaged* results obtained over the time period corresponding to one spin cycle clearly showed the effect of the synthetic jets on the lift as well as the side forces. The jet interaction effect is clearly seen when the jet is on during the spin cycle. However, these results show that there is an effect on the lift force (although reduced) for the remainder of the spin cycle *even when the jet is off*. This is a result of the wake effects that persist from one spin cycle to another. These time-accurate CFD results are first of its kind to show such an effect due to the wake interactions. The impulse obtained from the predicted forces for two jets seem to asymptote after 30 spin cycles.

The results have shown the potential of CFD to provide insight into the jet interaction flow fields and to provide guidance as to the locations and sizes of the jets to generate the control authority required to maneuver a spinning munition to its target with precision. This research is at the forefront of technology in projectile aerodynamics area and represents a major increase in capability for determining the unsteady aerodynamics of munitions in a ***new area of flow control***. This research has shown that micro-adaptive flow control with tiny synthetic jets can provide an *affordable* route to *lethal* precision-guided infantry weapons.

ACKNOWLEDGEMENTS

This work was accomplished as part of a research project on Micro Adaptive Flow Control sponsored and jointly funded by the Defense Advanced Research Projects Agency (DARPA) and the U.S. Army Research Laboratory (ARL). The authors wish to thank Sukumar Chakravarthy from Metacomp Technologies for his expert technical advice. The scientific visualization work of R. Angelini of ARL and the computational support of the ARL Major Shared Resource Center are greatly appreciated. The authors also wish to thank the DOD High Performance Computing Modernization Program for selecting this research as a Grand Challenge Project and providing us with the massive number of computing hours and assets for successful completion of the project.

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